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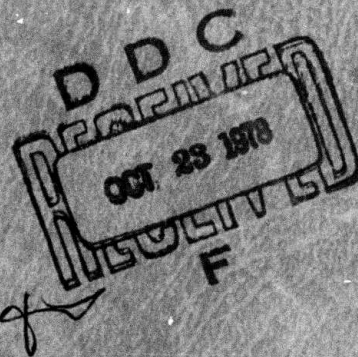
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LONGITUDINAL CIRCUMFERENTIAL VIBRATIONS
OF MAGNETOSTRICTIVE RINGS

by

Stanley L. Ehrlich

and

Harry Sussman

USL REPORT NO. 141

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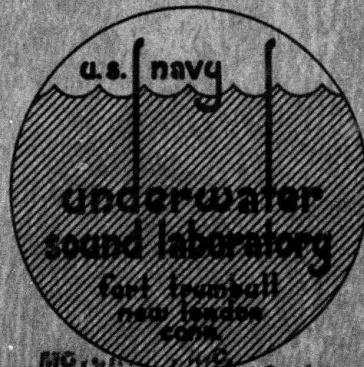
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ABSTRACT

An experimental investigation of the longitudinal circumferential vibrations of magnetostrictive rings is the subject of this report. Two methods of exciting several orders of these modes of vibration by means of magnetostriction are described. Sensitivity curves and radiation patterns of experimental transducers operating in these modes are presented.

AUTHORIZATION

650827·0550

LIST OF FIGURES

LONGITUDINAL CIRCUMFERENTIAL VIBRATIONS
OF MAGNETOSTRICTIVE RINGS

Stanley L. Ehrlich and Harry Sussman

As ordinarily constructed, a magnetostrictive ring or cylindrical trans-
ducer consists of a laminated or thin-walled magnetostrictive core and a
winding. This winding may be a toroidal one enclosing the core, or it may be
completely inside the ring as it is in transducers having an internal polarizing
magnet or a return flux path. The two types of winding are schematically dia-
grammed in Fig. 1.

In both types a current in the winding produces purely radial vibration,
and the maximum output voltage is produced by purely radial vibration of the
core. For this fundamental radial mode, the displacements in a thin-walled
ring are purely radial, and the strains are purely circumferential. The dis-
placement and the strain are uniform at all points.

Although several modes of vibration other than the fundamental radial mode
were known to exist and had been studied theoretically and experimentally,[1]
nothing had been published on efforts to excite these modes by means of mag-
netostriction. Of all the references examined, only one attributed an annoying
irregularity in the response of a hydrophone to a higher mode of vibration.[2]

An experimental investigation into the longitudinal circumferential class
of ring vibrations was conducted at the Underwater Sound Laboratory in April
and May of 1949.[3] This investigation was limited to developing methods of
exciting several orders of these modes and to measuring their responses and
directional characteristics. In longitudinal circumferential modes of vibration,
sections of the ring between nodes vibrate in a manner similar to the longitu-
dinal length vibration of a bar; one section of the ring elongates circumferen-
tially and the adjacent sections contract. The resulting radial contractions

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1. See, for example, A. E. H. Love, A Treatise on the Mathematical Theory of Elasticity, Cambridge Uni-
versity Press, London, 1943, pp. 287-292, 451-454, and W. Kuhl, "Measurements for the Theory of Natural
Oscillations of Circular Rings of Arbitrary Thickness," Akustische Zeitschrift, 1942, Vol. 7, pp. 125-
152, translated by S. L. Ehrlich and issued as USL Memorandum, Ser. 240-212, 1 December 1949 (UNCLASSIFIED).
2. This was discussed by W. B. Snow, J. W. Follin, and W. T. Harris in Transducer Research and Production
at the New London Laboratory, Summary Report of Division 6, NDRC, 25 May 1945 (CONFIDENTIAL).
3. A preliminary report on this investigation was made by S. L. Ehrlich in "Modes of Vibration of Ring
Transducer," USL Technical Memorandum, Ser. 240-049, 30 November 1949 (CONFIDENTIAL).
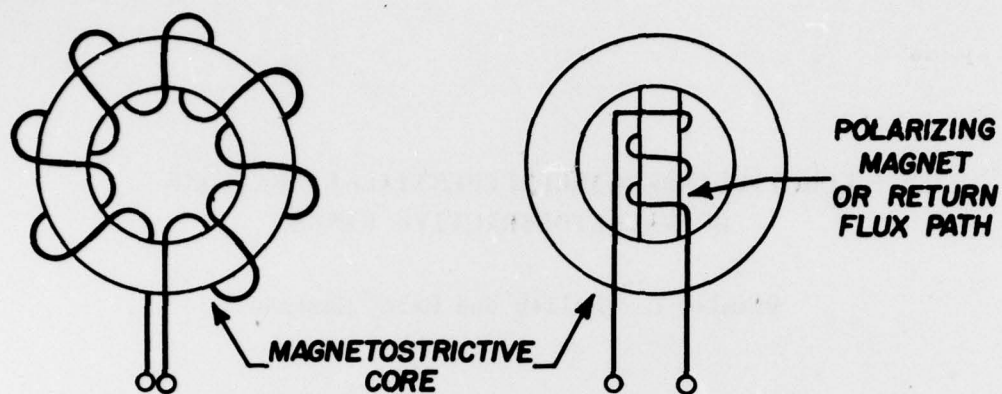
Fig. 1 – Schematic Diagram of Two Types of Windings
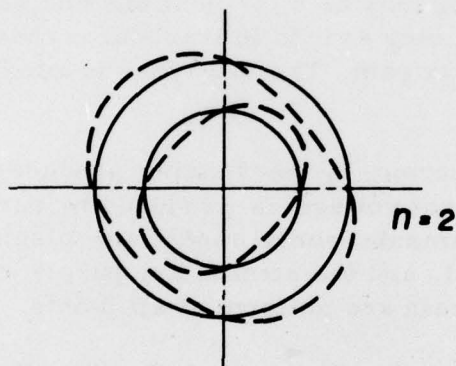

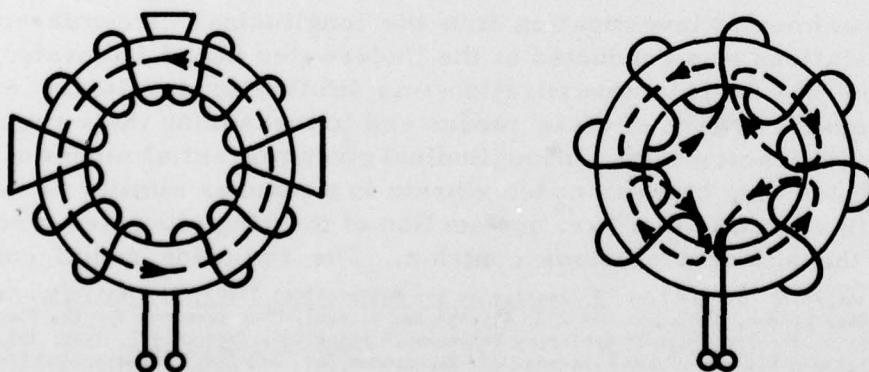Fig. 2 – Exaggerated Representation of the Longitudinal Circumferential Mode Having Four Nodes

Fig. 3 – Schematic Diagram of Two Methods of Exciting Longitudinal Circumferential Modes

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and expansions provide the acoustical coupling to the water. An exaggerated representation (see Fig. 2), in which dotted lines show the displaced position, illustrates the mode having four nodes. The radial mode, which is currently used in transducer design, has no nodes and may be considered as the lowest mode of the longitudinal circumferential type.

The resonant frequency of a thin ring of small axial height vibrating in a longitudinal circumferential mode is given by Love as:[4]

$$f = \frac{1}{2\pi r} \sqrt{\frac{E}{\rho}} \sqrt{n^2 + 1}$$

where

        f = the resonant frequency,

        r = the mean radius of the ring, (cm)

        E = Young's modulus, (dynes/cm2)

        ρ = the density, and (gms/cm3)

        n = one half the number of nodes. (The number of nodes is always an even integer.)

Love also states, "The modes of vibration considered . . . would probably be difficult to excite."[5]

Actually, the writers found these modes very easy to excite magnetostrictively. Excitation required merely dividing a toroidal winding into equal sections, one for each node, and connecting adjacent sections in series opposition. The polarizing flux was left circumferential and unidirectional. Conversely, a single, full toroidal winding might have been used if the polarizing flux had been broken into as many sections as nodes and if its direction had been reversed in adjacent sections. In Fig. 3, a schematic representation of these two methods of excitation is shown for n = 2; dotted lines indicate the polarizing flux.

A winding concentrated at one point on the ring excited all modes of this class, and the relative amplitude of each mode varied with the driving frequency. Conversely, this winding produced output voltages for all longitudinal circumferential modes, provided it was not placed at a node of the mechanical vibration. For optimum results, a good flux return path should have been provided, but this was not done in the experiments under discussion.

4. See Love, op.cit., pp. 452-453.
5. See Ibid., p. 454.

The open-circuit sensitivity curves and the radiation patterns for the radial mode (n = 0) and the modes for which n = 1 to n = 4 are presented in Figs. 4 through 8. The scale of the radiation patterns in this article is 10 db per division. As expected, the change in phase of the vibration at each node was responsible for a null at each of these points in the directivity patterns. These patterns and the responses were measured with a ring stack having an outer diameter of 2-3/4 inches, a wall thickness of 0.200 inch, and a height of 1/2 inch. The laminations were 10-mil Permendur annealed for one hour at 500° C. in hydrogen. A toroidal winding of 12 separate sections was used, and these were interconnected in such a way as to excite each mode. A schematic diagram of the connections is given in each pattern.

In Fig. 9 is the open-circuit voltage response of a similar ring stack which had a winding concentrated at one point in order to excite all modes. Because of the poor AC magnetic flux circuit, the directivity patterns (see Figs. 10 through 13) have the expected shape only in the angular region near the winding.

The measured resonant frequencies agreed fairly well with those calculated from the formula. However, because of the small axial dimension, a component of the radiation impedance increased the effective mass of the ring; this contribution was frequency dependent. The effective electromechanical coupling coefficients decreased, as expected, with increasing n because the leakage
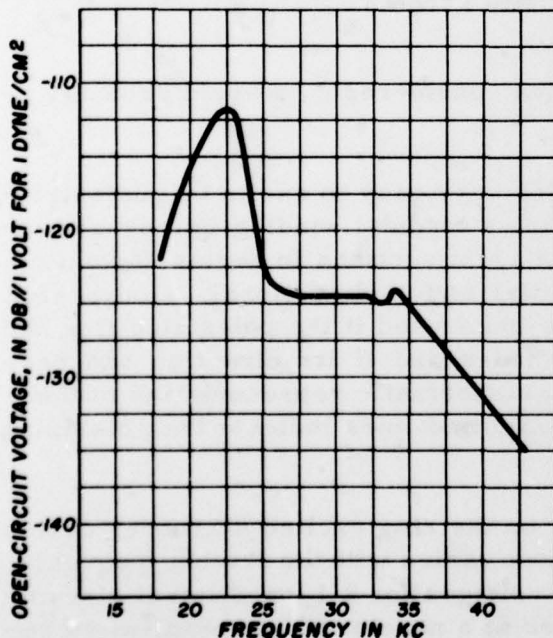

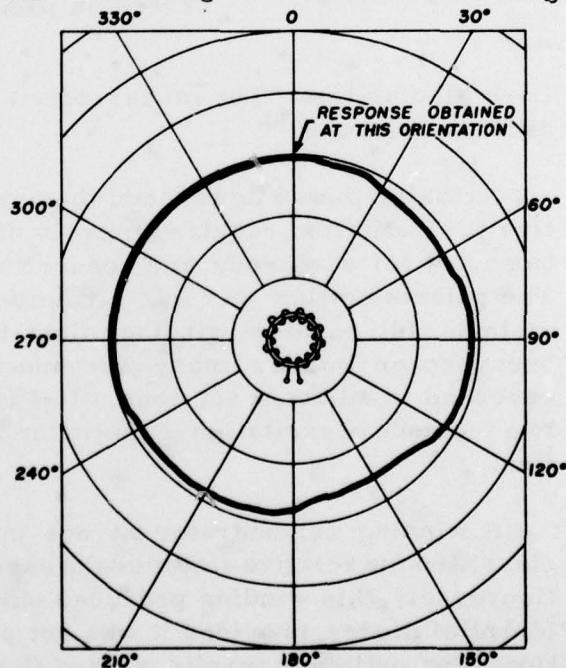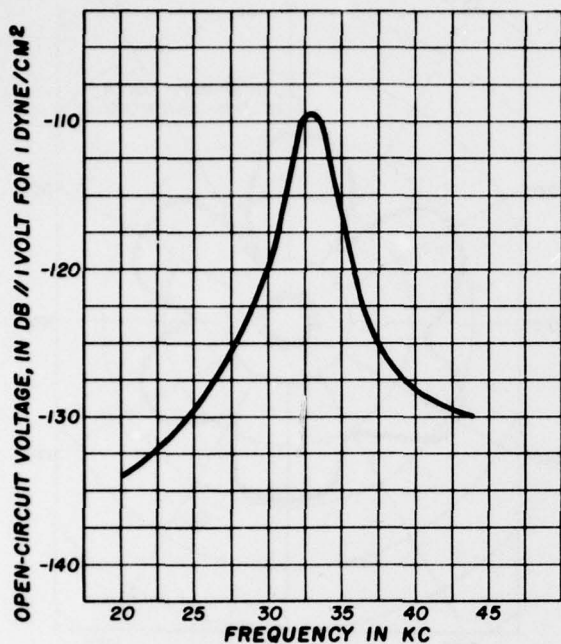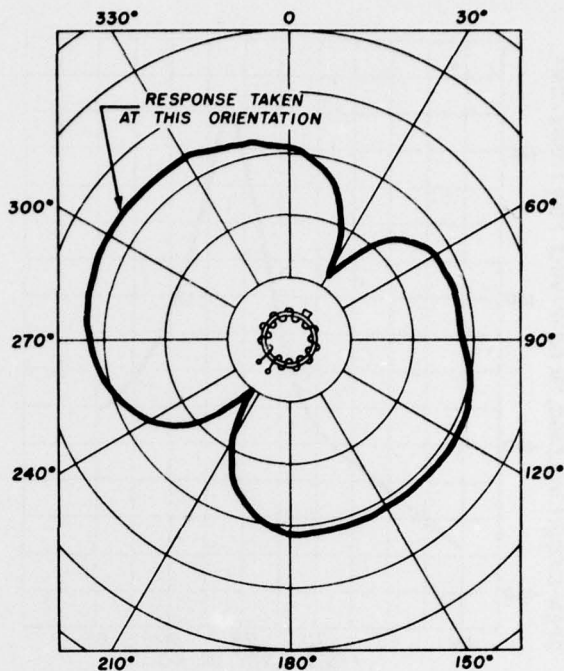Fig. 4A - Open-Circuit Voltage Response

Fig. 4B - Receiving Directivity Pattern Taken at 22 kc and Schematic Drawing of Winding

Fig. 4 - Sensitivity and Radiation Pattern of Ring Stack Operating in Fundamental Radial Mode

Fig. 5A - Open-Circuit Voltage Response

Fig. 5B - Receiving Directivity Pattern Taken at 32.9 kc and Schematic Drawing of Winding

Fig. 5 - Sensitivity and Radiation Pattern of Ring Stack Operating in Longitudinal Circumferential Mode Having Two Nodes
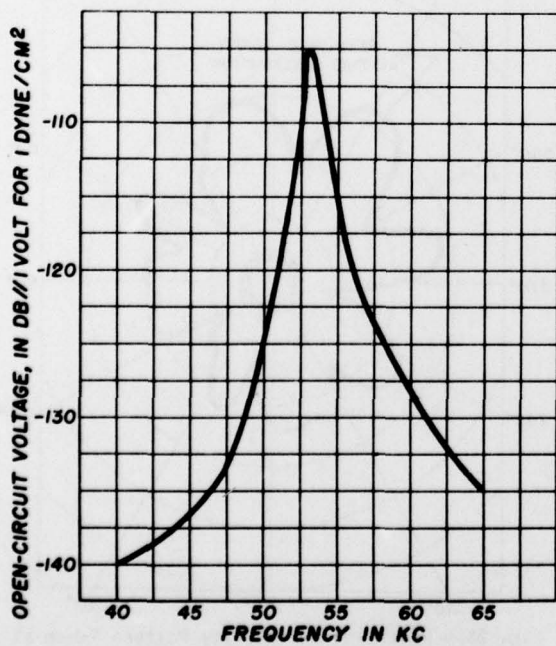

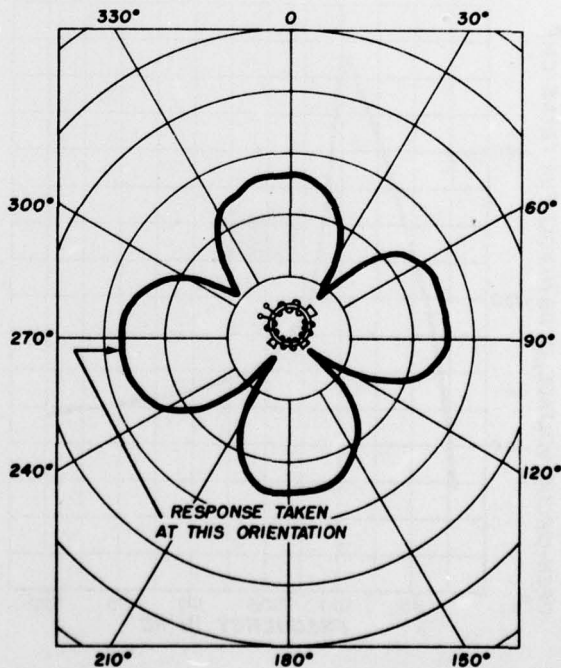Fig. 6A - Open-Circuit Voltage Response

Fig. 6B - Receiving Directivity Pattern Taken at 53.8 kc and Schematic Drawing of Winding

Fig. 6 - Sensitivity and Radiation Pattern of Ring Stack Operating in Longitudinal Circumferential Mode Having Four Nodes
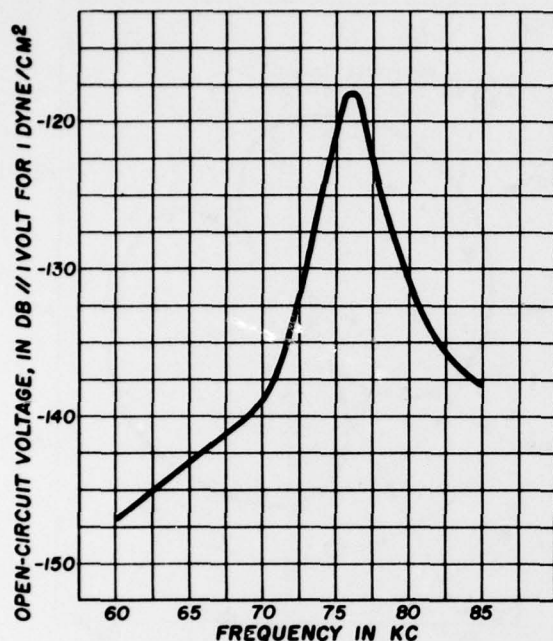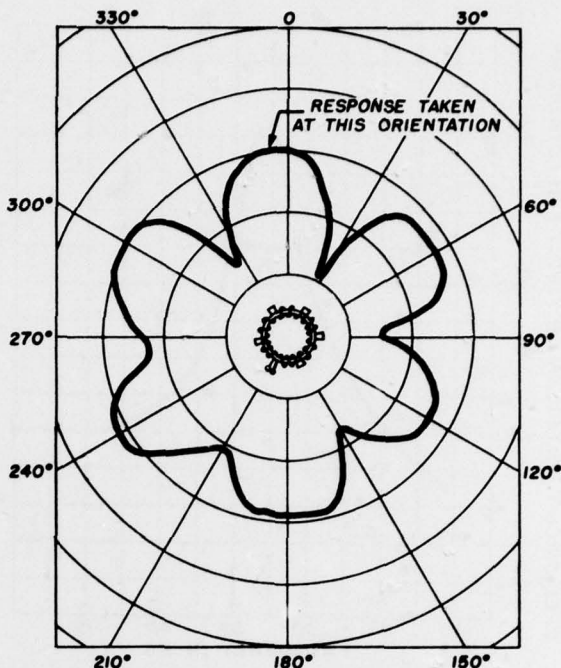
Fig. 7A - Open-Circuit Voltage Response

Fig. 7B - Receiving Directivity Pattern Taken at
76 kc and Schematic Drawing of Winding

Fig. 7 - Sensitivity and Radiation Pattern of Ring Stack Operating in Longitudinal Circumferential
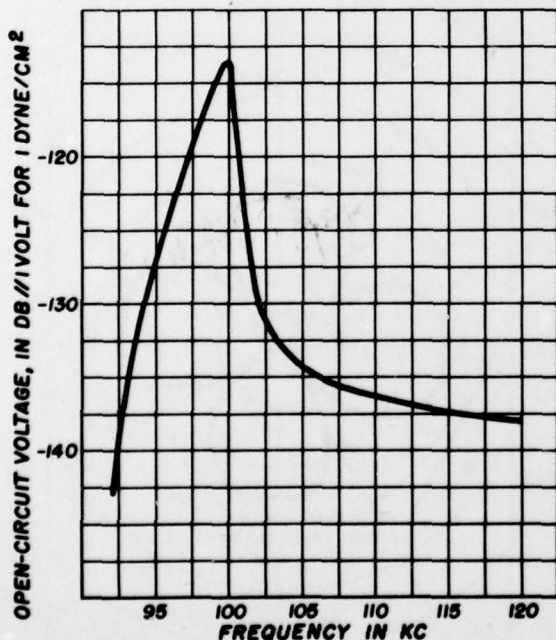Mode Having Six Nodes

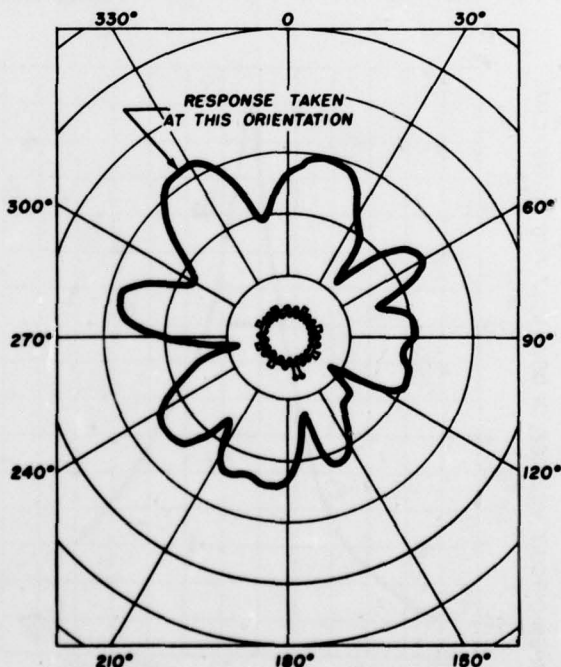Fig. 8A - Open-Circuit Voltage Response

Fig. 8B - Receiving Directivity Pattern Taken at
99.8 kc and Schematic Drawing of Winding

Fig. 8 - Sensitivity and Radiation Pattern of Ring Stack Operating in Longitudinal Circumferential
Mode Having Eight Nodes

flux became progressively greater with n. Values computed from impedance measurements ranged from 0.133 for n = 0 to 0.028 for n = 4. Although the acoustical coupling to the water appeared reasonably satisfactory, both the acoustical and the electromechanical couplings could have been improved by providing good flux return paths.

Incidental to the principal considerations of this investigation, it was found that pressure-release material placed in the proper regions around the circumference of a ring controlled the

Fig. 9 - Open-Circuit Voltage Response of Ring Stack with Winding Concentrated at a Point

number, the size, and, to some extent, the shape of the directivity lobes. Corprene 1/16 inch thick, for example, was used to cover the 90-degree arcs of alternate lobes produced by a scroll operating in the n = 2 mode. The result was that the lobes covered with Corprene were reduced by 10 db, as shown in Fig. 14. The other lobes were about 15° wider between nulls, but their beam width, approximately 60° between -6 db points, was not appreciably changed by the Corprene.
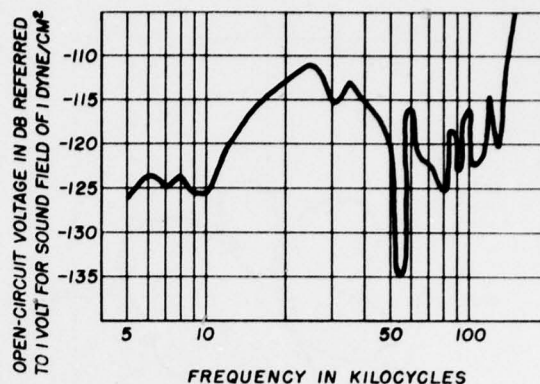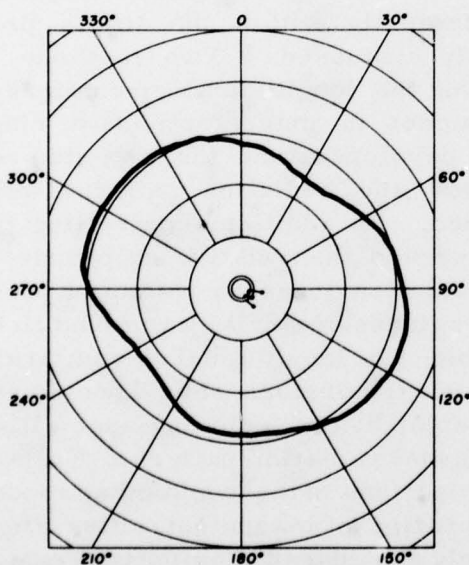
Fig. 10 - Receiving Directivity Pattern of Ring Stack with Winding Concentrated at a Point, Longitudinal Circumferential Mode Having Two Nodes, 36.5 kc
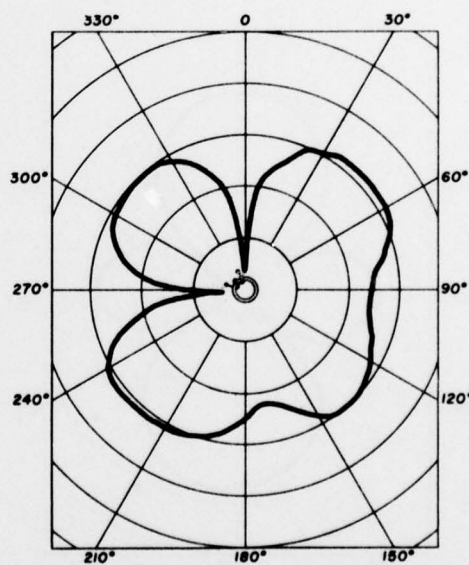
Fig. 11 - Receiving Directivity Pattern of Ring Stack with Winding Concentrated at a Point, Longitudinal Circumferential Mode Having Four Nodes, 58.25 kc
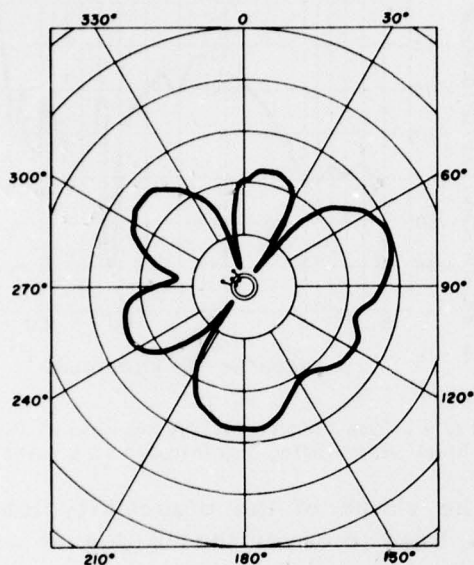
Fig. 12 - Receiving Directivity Pattern of Ring Stack with Winding Concentrated at a Point, Longitudinal Circumferential Mode Having Six Nodes, 83.25 kc
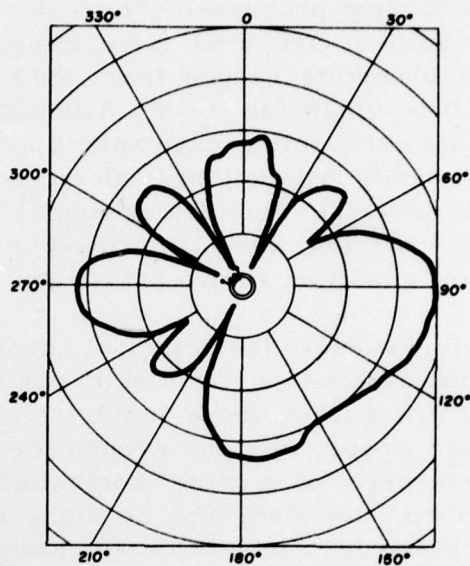

Fig. 13 - Receiving Directivity Pattern of Ring Stack with Winding Concentrated at a Point, Longitudinal Circumferential Mode Having Eight Nodes, 108 kc
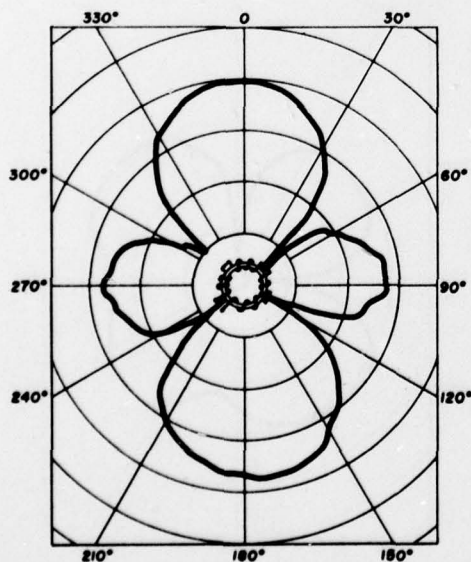

Fig. 14 - Receiving Directivity Pattern of Scroll Having Alternate 90-degree Arcs Covered with 1/16-inch Corprene, Longitudinal Circumferential Mode Having Four Nodes, 52 kc

This investigation was completed satisfactorily within the limits previously discussed. Two methods of exciting the longitudinal circumferential modes in magnetostrictive rings were developed, and the expected responses and radiation patterns were verified. In addition, controlling the number and the relative amplitude of the radiation lobes by means of pressure-release material was found to be feasible. The longitudinal circumferential modes, therefore, should prove useful in applications requiring specialized or unusual radiation patterns. Further investigations of these and other modes of vibration of magnetostrictive rings not only should lead to important extensions of existing transducer theory but also should result in information and techniques valuable for specific applications.